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A Systematic Study of the Effects of Crust and Upper Mantle Structure on Regional Seismograms

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13. ABSTRACT *(Maximum 200 words)* As part of a broader effort to invert for Eurasian crust and upper mantle structure, a study has been undertaken to investigate the effects of structural model variations on regional synthetic seismograms. The intent of this study is to produce regional synthetic seismograms that approximately match the observed data so that the inferred structural models can be used as starting points in a formal inversion proceedure. Using laterally homogeneous structural models we have systematically varied velocity-depth functions down to about 500 km depth and compared synthetic seismograms to data out to about 2000 km distance. Differential seismograms were used to infer relationships between structural parameters and the resulting seismograms. By using standard Eurasian crust and upper mantle structural models and introducing velocity randomization, it is possible to produce synthetic seismograms that show all of the regional phases complete with attendant coda. However, the synthetic seismograms show energetic P_g and S_n phases at distances above 1000 km that are often not present in the data. The S_n phase can be reduced by suitable upper mantle velocity profiles. The reduction of P_g in the synthetics is more difficult which indicates that lateral scattering may be reducing P_g amplitudes without adversely affecting L_g.

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A Systematic Study of the Effects of Crust and Upper Mantle Structure on Regional Seismograms

by

Danny J. Harvey

1. Introduction

As part of a broader effort to invert for Eurasian crust and upper mantle structure, a study has been undertaken to investigate the effects of structural model variations on regional synthetic seismograms. The intent of this study is to produce regional synthetic seismograms that approximately match the observed data so that the inferred structural models can be used as starting points in a formal inversion procedure. Another purpose for this study is to identify to what extent different modeling techniques can be used to adequately represent the observations.

We are particularly interested in using laterally homogeneous modeling procedures since they are computationally efficient and accurate, given the assumption of 1D structure. This issue of computational efficiency is not a minor point. The process of inferring source and structural parameters, whether using formal inversion procedures or systematic studies, requires a large number of forward evaluations. On the other hand, we know that the earth is not laterally homogeneous and it is important to identify the inadequacies of full waveform modeling using 1D structures. In this study we hope to gain understanding about the basic physical processes that are important for regional seismic wave propagation and we want to determine the fundamental limitations of 1D modeling techniques.

2. Research Accomplished

The data we used in this study comes from three sources and we have concentrated on the USSR Joint Verification Experiment (JVE) nuclear shot that took place on September 14, 1988 at the Semipalatinsk test site in Kazakhstan. The first set of data sources are the IRIS high frequency surface instruments at Chusal (CHS), Arti (ARU) and Obninsk (OBN). The second set of sources were portable high frequency instruments that were placed at Karasu (KSU), Karkaralinsk (KKL) and Bayanaul (BAY) and the third data source consists of hand digitized analog records recorded by Soviet observatories at

ARU, OBN, Talaya (TLY) and Norilsk (NRI).[1] Figure 1 shows a record section plot of the vertical component IRIS and portable digital instrument recordings after application of a low pass filter and decimation to 1 Hz nyquist frequency. The useful frequency range is 0.1 to 1.0 Hz. The digitized Soviet data after similar filtering and decimation is shown in figure 2.

Although the instrument responses for the analog records are somewhat different from those of the digital instruments, we can still see certain basic characteristics of the waveforms.

1. Other than the first P arrival, the only consistent arrival is L_g which is characterized as an emergent arrival with a long coda. We should point out that L_g is not always apparent from other test sites or at stations from the Kazakh test site that are further away.

2. The S_n arrival, which becomes the direct upper mantle S arrival at the longer distances, can be seen on some of the records (CHS and ARU), but it is small.

3. There is no obvious P_g arrival. It could be hidden in, or contributing to, the coda

[1] The digitized analog Soviet data was obtained through a joint US-Soviet seismic data exchange agreement. These data were originally heliocorder records that were hand digitized by a US contractor.

associated with the first P arrival.

4. There is no appreciable Rayleigh wave in this frequency band for the stations at distances greater than 250 km.

We used three methods for computing synthetic seismograms for comparison with the data: the locked mode method of Harvey,[2] the reflectivity method[3] and the WKBJ ray theoretical method of Chapman and Dey-Sarkar.[4] Most of the complete seismograms were computed with the locked mode method with the reflectivity method used for periodic checks. The WKBJ ray theory was meant to be used as a very rapid initial check of candidate structural models. The synthetic seismograms were all computed to 1 Hz nyquist frequency and were filtered with the instrument responses and the same anti-aliasing filter used in the decimation of the data.

The structural models used in this study are shown in figure 3. We started with a "crude" model, shown in figure 3a, which consists of six homogeneous layers with discontinuities at 10, 50, 220, 410 and 700 km depth. The Q model for the "crude" structure was Q_α = 2000 and Q_β = 950 in every layer except the topmost layer where Q_α = 200 and Q_β = 95. A synthetic record section using the crude model is shown in figure 4. If we compare this with the data we can see that the crude model produces no appreciable L_g and it produces a direct S arrival that is much larger than in the data. If we try to increase the Q values in the topmost layer, a large Rayleigh wave appears and L_g is still much smaller than in the data.

Figures 5 through 10 show the synthetic record sections corresponding to the structural models shown in figures 3b through 3g. The base1 model is a layerized version of a model with smooth gradients within the crust, at the Moho and in the upper

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[2] Harvey, D. (1981). Seismogram synthesis using normal mode superposition: the locked mode approximation. *Geophys. J. R. Astr. Soc.* 66, 37-61.

[3] Luco, J. and Apsel, R. (1983). On the Green's functions for a layered half-space: Part I. *Bull. Seismol. Soc. Am.* 73, 909-929.

[4] Dey-Sarkar, S. K. and Chapman, C. H. (1978). A simple method for the computation of body-wave seismograms. *Bull. Seismol. Soc. Am.* 68, 1577-1593.

mantle.The base2 model is similar to base1 except that a weak low velocity zone has been introduced at about 100 km depth, the upper mantle gradients have been decreased and gradients at the upper mantle discontinuities have been added. The base3 model, although unrealistic, was an attempt to minimize the direct S phase by using a completely smooth V_s distribution throughout the upper mantle.

In a previous study we determined that using a vertically randomized velocity distribution in the crust produced synthetic seismograms that show many of the features that we see in the data especially in the early parts of the wavetrain. The ran1-base1, ran1-base2 and ran1-base3 (figures 3e, 3f and 3g) structural models are combinations of the upper mantle structures of base1, base2 and base3 with a vertically randomized version of the crust.

If we look at the synthetic record sections of figures 4, 5, 6 and 7, which all correspond to smooth or large-scale blocky structural models, we see many large amplitude impulsive arrivals. The direct upper mantle S arrival is particularly large. We took some time to understand the nature of this arrival in the synthetic seismograms. We were using pure explosion sources at 630 m depth for all of the synthetic seismograms so the S arrival is generated entirely by P toS conversions predominately at the free surface. By comparing ray theoretical arrivals with those from the complete seismogram synthesis codes we were able to determine that the direct S arrival is a combination of a normal P to S conversion at the free surface along with a strong diffraction arrival that is generated by the small radius of curvature of the P wave front as it is reflected at the free surface. In order to represent this diffraction arrival in the ray theoretical code we added a vertical vector point force at the free surface that was time delayed by the P travel time from the explosion source at 630 m depth to the surface.

The data shows weak or nonexistent direct S arrivals which represents a major discrepancy between the data and the synthetics. From previous studies we know that there is evidence that underground nuclear explosion arrivals generated by free surface conversions are weaker in the near source region than theory predicts.[5] However, this effect is not normally strong enough to explain the difference the we see here between the synthetic seismograms and the data. If we look to upper mantle intrinsic attenuation, a simple calculation yields a Q_β value of about 100 that would be necessary to bring down the direct S arrival amplitudes to be consistent with the data and this value of upper mantle Q is probably unreasonable and at odds with the Q estimates from whole earth inversion studies for the central Asian shield region.

As an alternative mechanism for the reduction of the direct S arrival amplitude we have investigated near surface linear elastic scattering by introducing a large number of thin crustal layers with a random component to the velocity distribution which presents a broad-scale vertical scattering environment to the upper mantle arrivals as they pass through the crust. Figures 8, 9 and 10 show synthetic record sections with crustal randomized versions of the structures represented in figures 5, 6 and 7 respectively. The crustal scattering in the randomized models has caused a number of effects.

1. The direct S arrival is consistently reduced in amplitude. In some cases, such as at CHS, this reduction is substantial and the seismograms for the randomized models conform to what we see in the data.
2. The direct P arrival is able to pass through the randomized crustal layers with only a small reduction in amplitude which is consistently with the data.
3. There is a tendency for all impulsive arrivals to be "blurred" out to produce wavelet groupings followed by coda. This is a characteristic that we see in the data.
4. Although it is not readily apparent in the figures, the total L_g energy level increases with the randomized models.

[5] This is normally attributed to non-linear effects in the region above the explosion which effectively create an extremely low Q zone between the explosion and the surface.

A closer comparison of the data with all of the synthetic seismograms at four stations can be seen in figures 11 through 14. The crustal randomization mitigates, at least to some extent, the problem with the direct S arrival, however there remain substantial differences between the data and the synthetics especially regarding L_g and the Rayleigh surface wave. By using differential seismograms we have determined that L_g for these crustal models propagates in the upper 10 km of the crust, in the same general region where the 0.5 Hz Rayleigh wave is appreciably energetic. Attempts to attenuate the Rayleigh wave with suitable Q models also causes L_g to be attenuated. This can be clearly seen when we compare the crude model, where the Q values were low all the way down to 10 km depth, to the basel model, where the Q values were low only to several km depth. If we compare L_g to P amplitude ratios of the data to those of the synthetics we find that except for station KKL, the data has consistently higher values than the synthetics suggesting that, if anything, the upper crust Q values for the synthetics are too low. At the same time the data shows no sign of 0.5 Hz Rayleigh waves for the stations at distances more than 1000 km, suggesting that the upper crust Q values for the synthetics are too high.

If we look at the comparison for station KKL (figure 11), which is at a distance of about 250 km, the data shows a large and dispersed Rayleigh wave and a small L_g arrival. This is a station where the L_g to P amplitude ratio is higher for the synthetics than for the data and where the data shows a Rayleigh wave that has approximately the same amplitude as that of the synthetics. The big difference between the data and the synthetics is the dispersed nature of the Rayleigh wave in the data compared to the relatively impulsive nature of the Rayleigh wave in the synthetics. The group velocity range corresponding to the observed Rayleigh wave dispersion is about 3.0 to 2.4 km/sec. This sort of dispersion at such a small distance is difficult, if not impossible, to produce with laterally homogeneous modeling techniques using reasonable structural models. We think that the observed dispersion in the Rayleigh wave at KKL is likely due to lateral scattering mechanisms that fall into two basic categories: 1) large scale multi-pathing of the fundamental Rayleigh wave from different azimuths at the receiver and 2) small to medium scale scattering of the fundamental Rayleigh wave into higher modes along the entire propagation path.

If small scale scattering of the Rayleigh wave is not important, then we would expect to see the Rayleigh wave at the larger distances except with "scrambled" dispersion characteristics, like we do at KKL. If small scale scattering is important, then the Rayleigh wave would be continuously scattered into other modes along its propagation path which would effectively attenuate it as it propagates. When the Rayleigh wave impinges upon a small subsurface scattering region, body wave energy would be radiated which would likely be at the S wave velocity of the upper crust, i.e. the L_g velocity. We think that there is a strong tendency for the high frequency Rayleigh wave to be scattered into L_g which attenuates the Rayleigh wave and boosts the L_g arrival and this hypothesis is consistent with the differences we see between the data and the laterally homogeneous modeling results.

The lateral scattering of a well organized surface wave into a highly focused waveguide arrival points out the inadequacies of representing random scattering with an effective "scattering" Q value. The scattering Q value necessary to reduce the Rayleigh wave amplitude consistent with the data also clobbers L_g. In this case the effective scattering Q value is different for the Rayleigh wave and L_g even though they occupy the same depth and frequency range. In fact it may be that the scattering Q for L_g is negative, since L_g is the beneficiary of Rayleigh wave energy along with other forms of scattered energy. If this representation of L_g is accurate then we could consider L_g to be a sort of "garbage can" arrival that picks up energy scattered from other arrivals and focuses it along the upper crust waveguide.

3. Conclusions

We have compared regional data recorded during the Soviet JVE with synthetic seismograms for a number of hypothetical structural models using laterally homogeneous modeling techniques. Our intent was to determine which parts of the waveforms could be adequately represented by these techniques, to identify where lateral scattering plays a critical role in the wave propagation and to infer structural models that can be used as starting values in a formal inversion procedure. Out conclusions from this study are as follows.

1. The only clear and consistent arrivals in the data are the first P arrival and L_g. A weak direct S arrival can be seen occasionally. There is no evidence of a Rayleigh wave at distances above 1000 km.

2. Laterally homogeneous modeling does a fairly good job of representing the first P arrival and, to a lesser extent, the first S arrival.

3. Vertical randomization of the crust is necessary to smooth out impulsive arrivals that we do not see in the data and to help capture S energy within the crust before it has a chance to propagate into the mantle.

4. Although most reasonable laterally homogeneous structural models will produce an L_g arrival, it is difficult to match the observed amplitude. Attempts to adjust upper crust Q values to boost L_g has the undesirable side effect of boosting the Rayleigh wave amplitude.

5. A plausible hypothesis to explain the differences in L_g and Rayleigh wave amplitudes between the synthetics and data is that small to medium scale lateral scattering of the Rayleigh wave into L_g is occurring along the entire Rayleigh wave propagation path.

6. The L_g arrival may be a seismic "garbage can" that naturally picks up and focuses energy that has been scattered, either vertically or laterally, from all other waves

that pass through the upper crust.

Our recommendations for future work are as follows.

1. In order to explain Rayleigh wave and L_g amplitudes at regional distances, Rayleigh wave to L_g lateral scattering needs to be investigated. It is likely that either a mode coupling method must be used to model this or numerical modeling methods, such as 2D or 3D finite difference, must be used.

2. The role of vertical randomization in the upper mantle needs to be studied. Although we would not expect the random characteristics of upper mantle velocity distributions to be the same as those in the crust, it would be reasonable to expect some effectively random component to the velocity distributions. Upper mantle randomization would help to further smooth out impulsive arrivals and to effectively defocus strong triplications.

3. It will be highly desirable to develop methods for mapping structural and source statistical parameters into observed statistics, such as RMS L_g measurements.

4. Contributing Researchers

The following individuals contributed to the research described in this report.

Dr. Roger Hansen, Air Force Technical Applications Center, Patrick AFB, FL

5. Related Contracts and Publications

A companion contract, "Studies of High Frequency Regional Discriminants", F19628-90-K-0023, provided partial support for some results presented in this report.

The following publications were produced in part with support from this contract.

Harvey, D., and Hansen, R., 1991, A Systematic Study of the Effects of Crust and Upper Mantle Structure on Regional Seismograms, Proceedings of the Thirteenth Annual PL/DARPA Seismic Research Symposium, J. Lewkowicz, and J. McPhetres, ed.

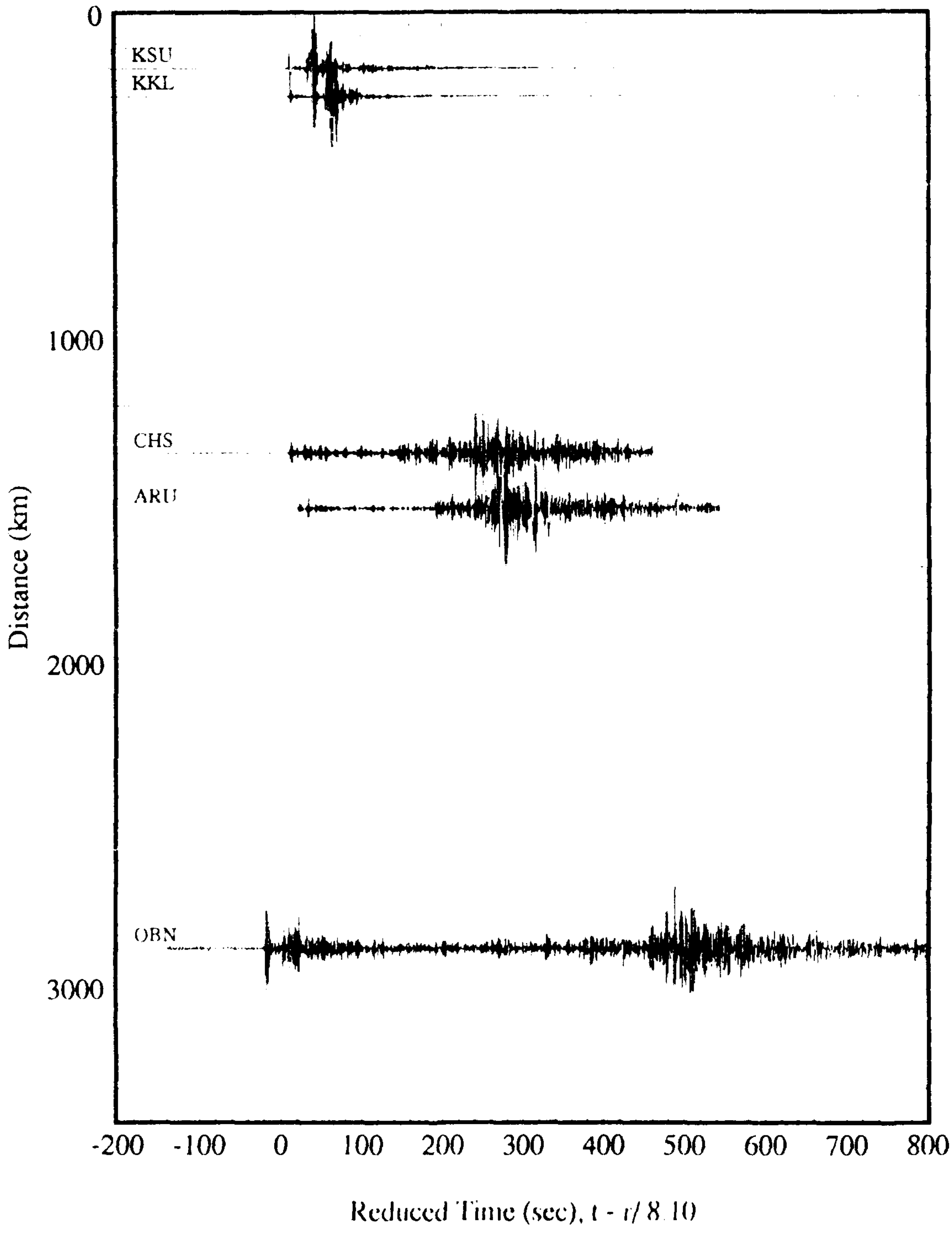

Figure 1. Digital vertical component records from the IRIS and portable instruments for the Soviet JVE after decimation to 1 Hz.

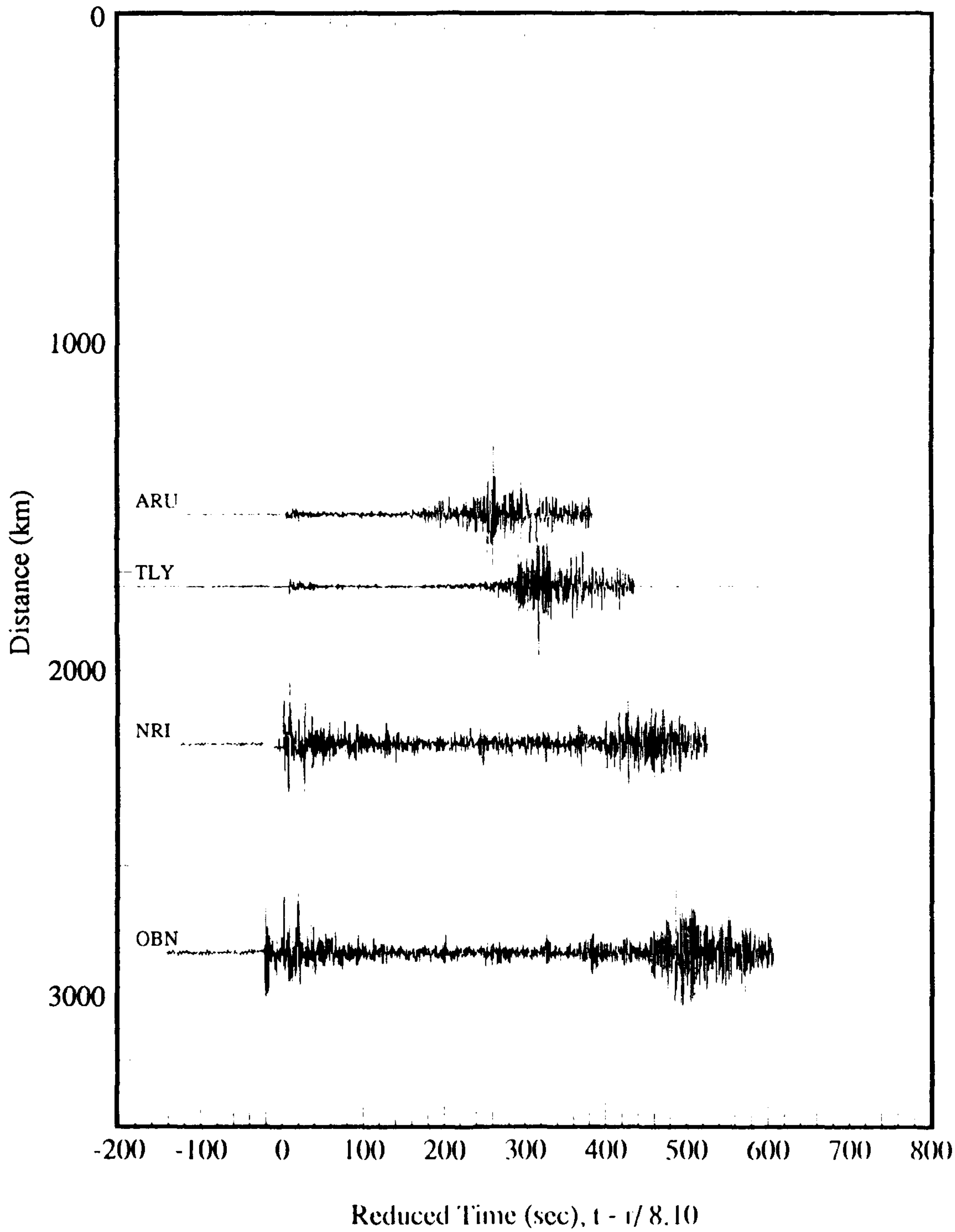

Figure 2. Analog vertical component records from the Soviet instruments for the Soviet JVE after decimation to 1 Hz.

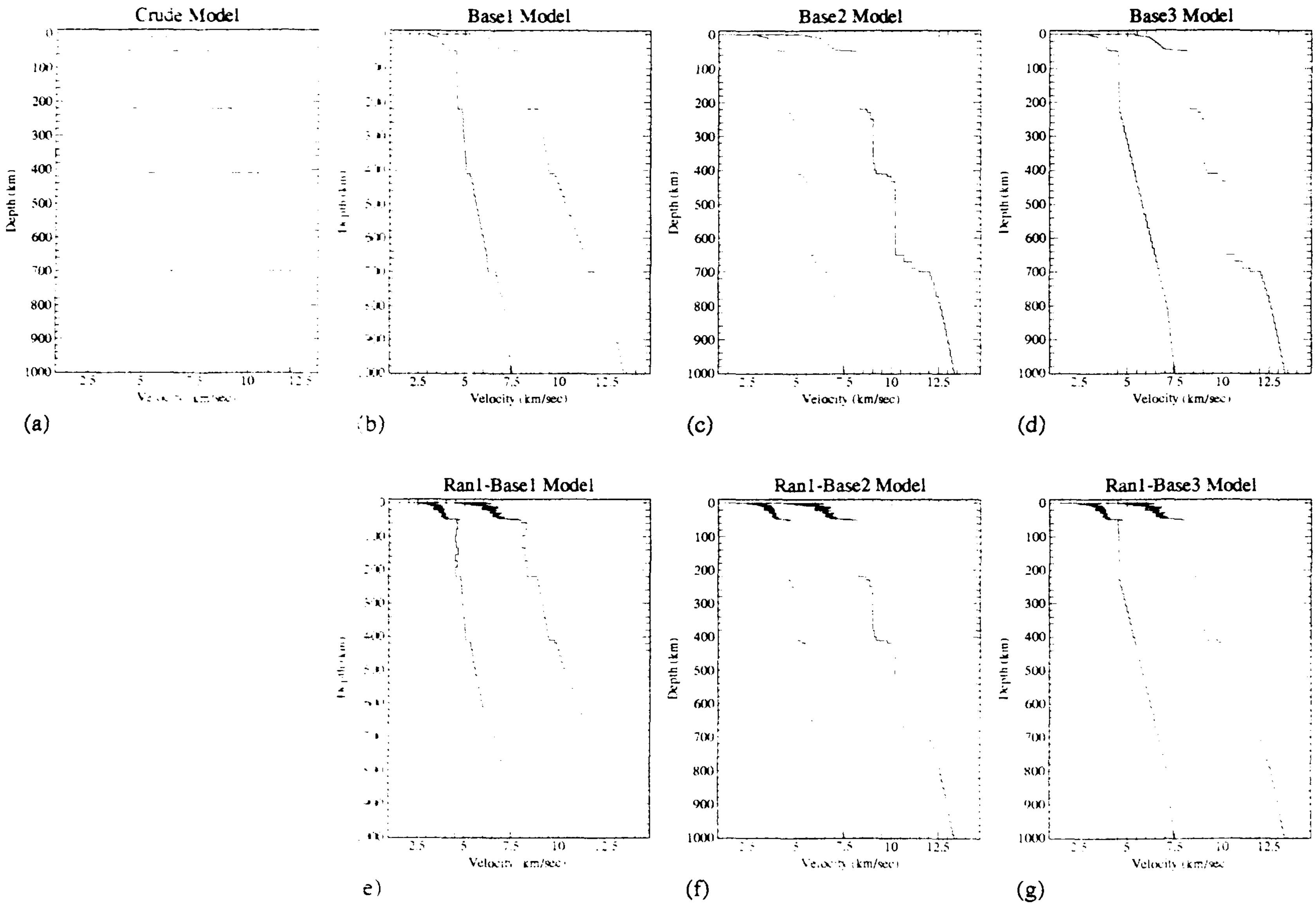

Figure 3 P and S wave velocities for the structural models used in this study.

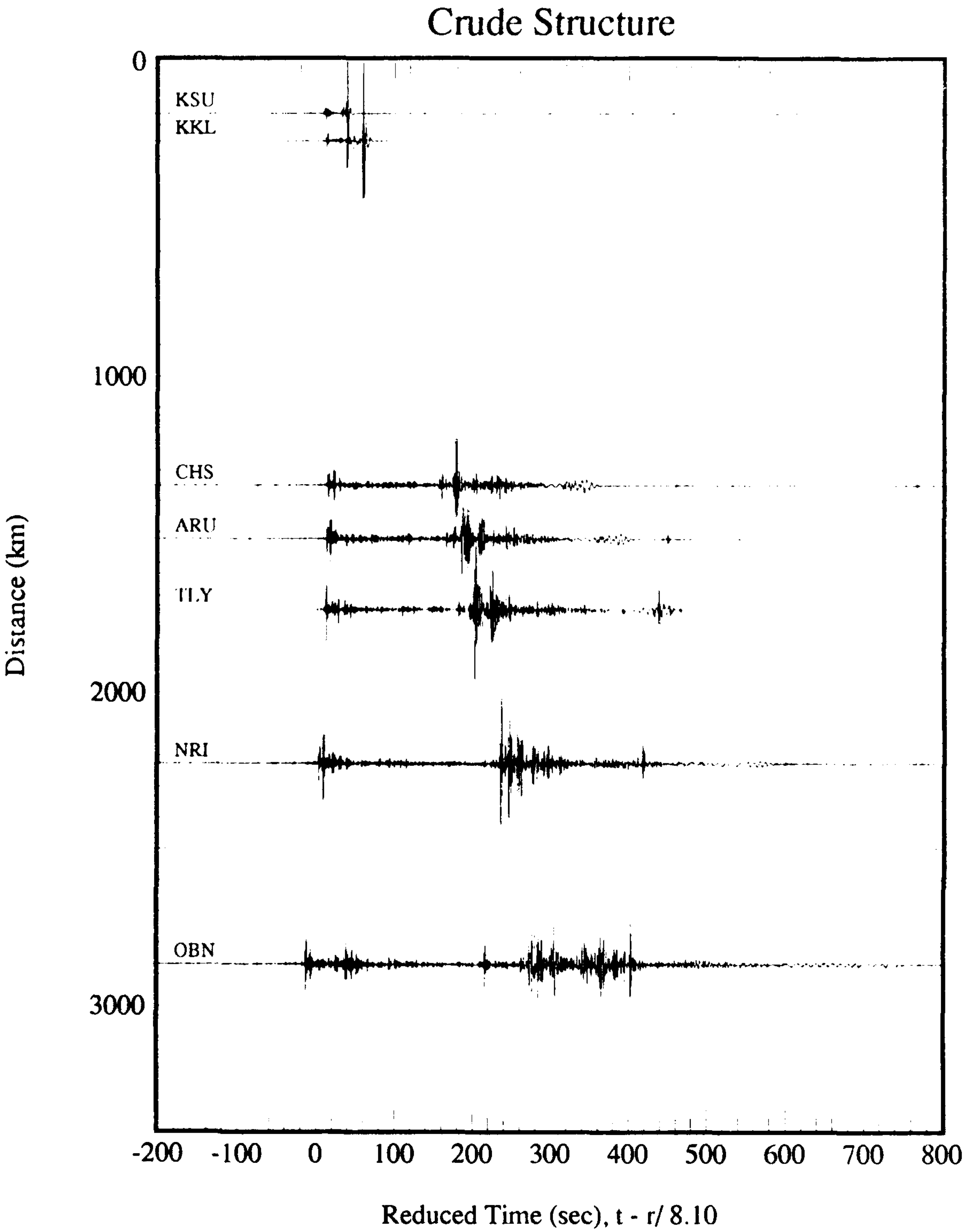

Figure 4. Synthetic seismograms for the structural model shown in figure 3a.

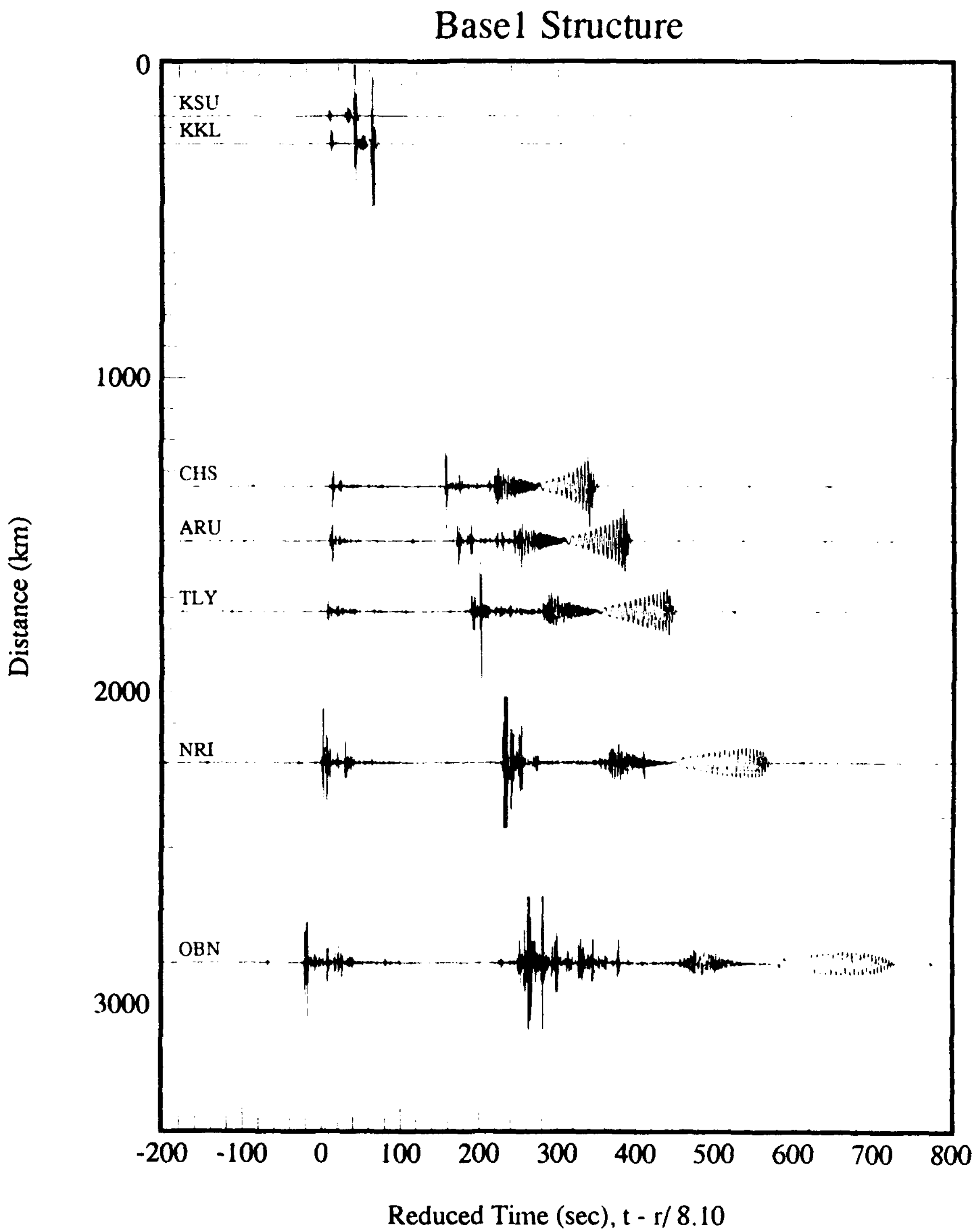

Figure 5. Synthetic seismograms for the structural model shown in figure 3b.

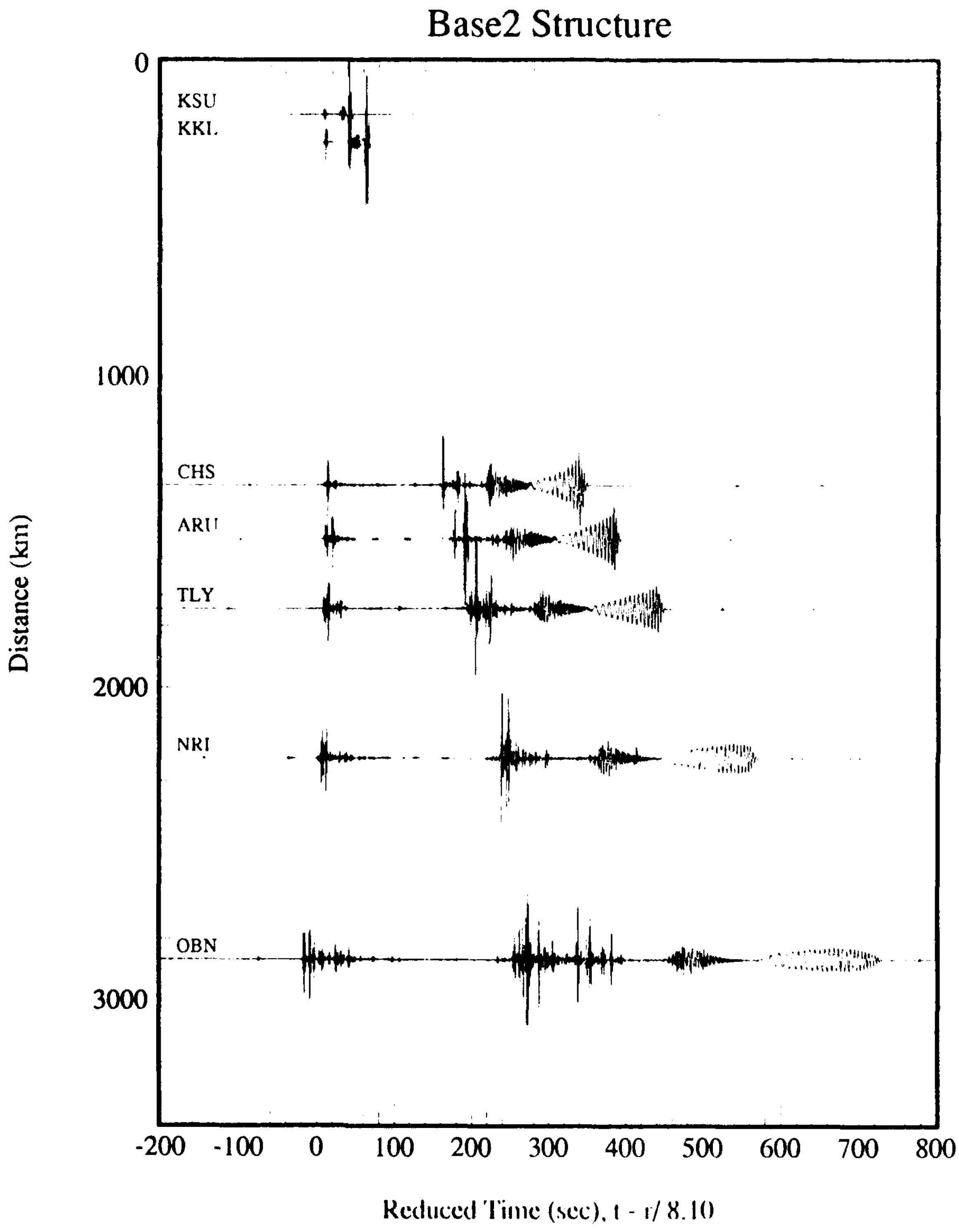

Figure 6. Synthetic seismograms for the structural model shown in figure 3c.

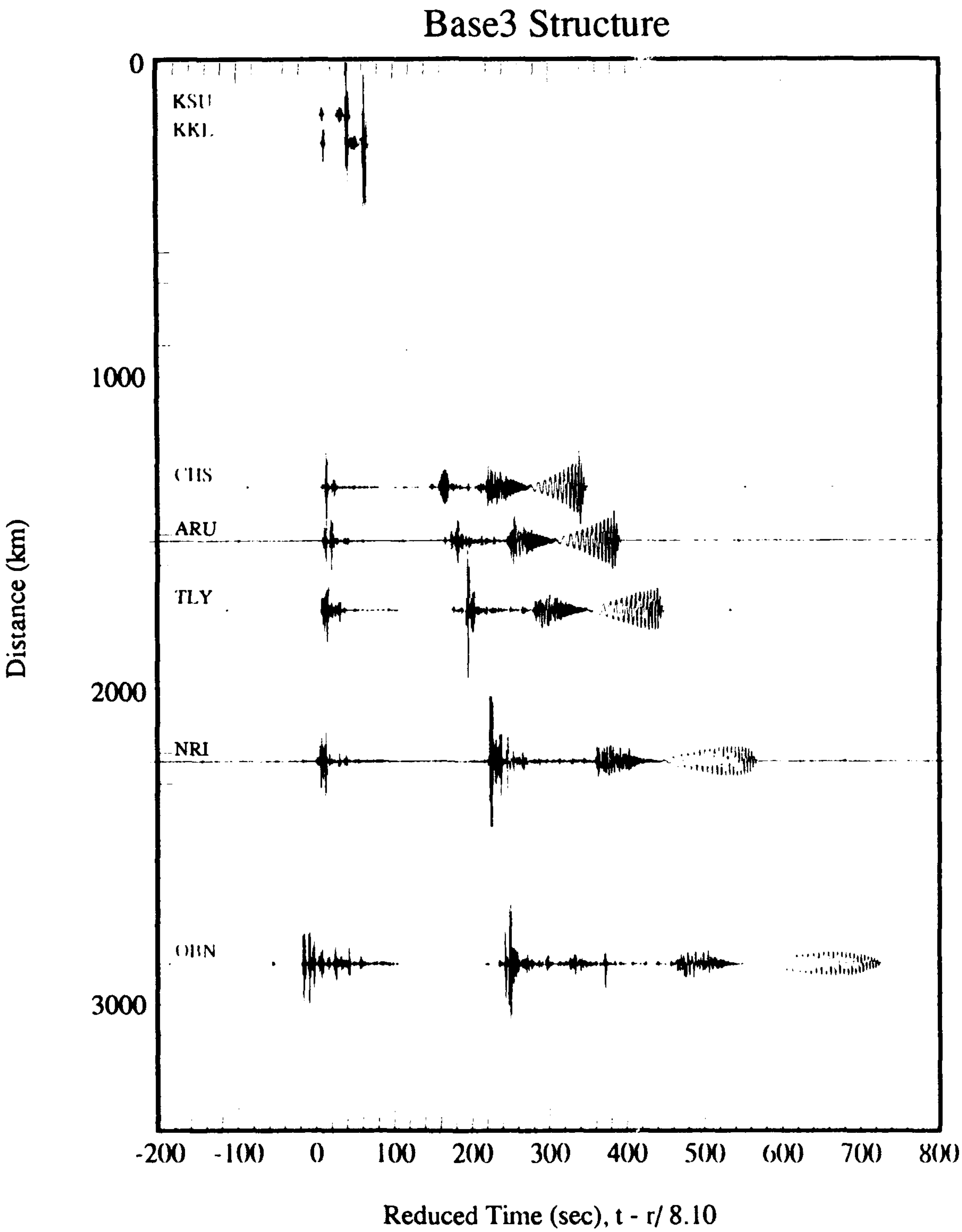

Figure 7. Synthetic seismograms for the structural model shown in figure 3d.

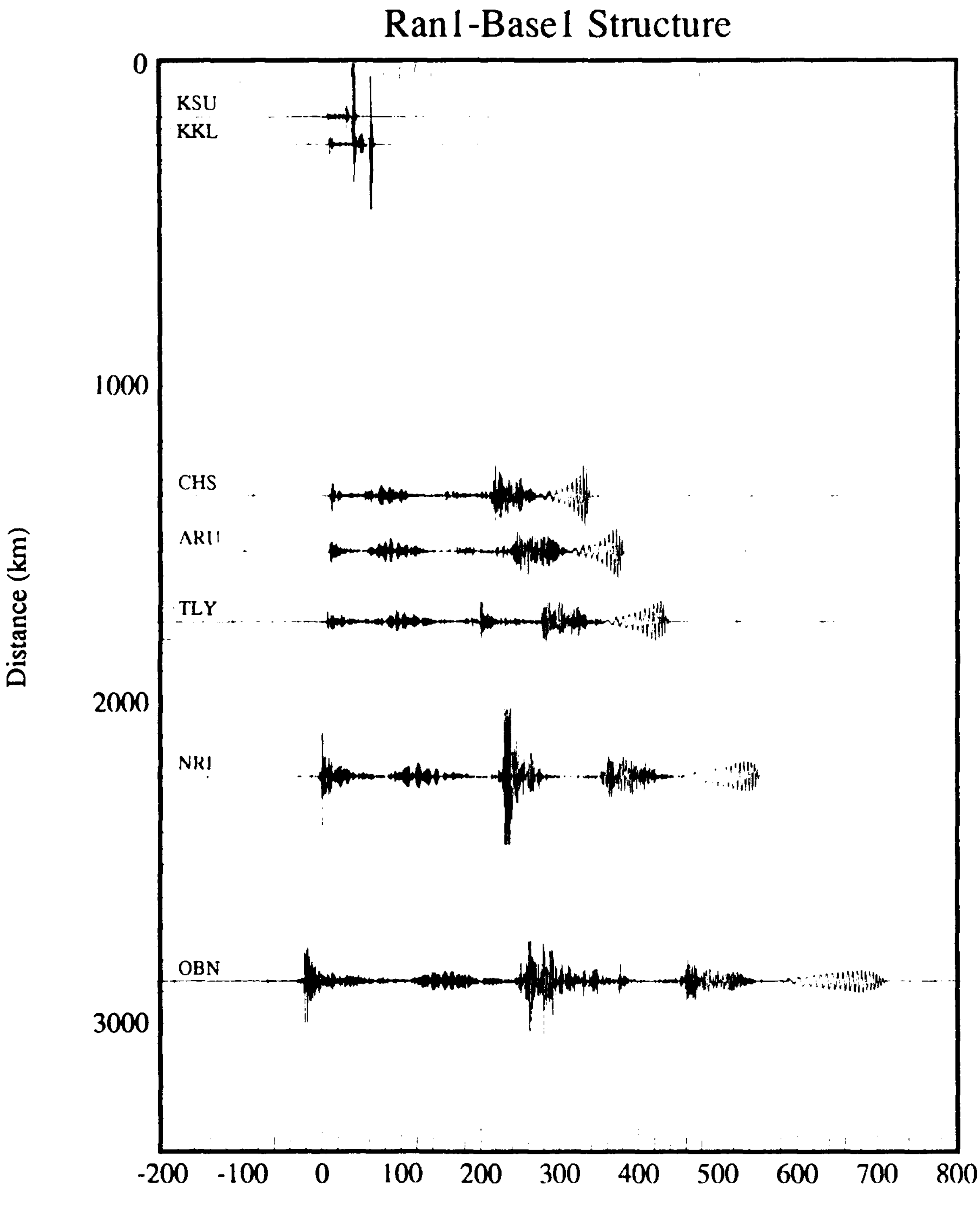

Figure 8. Synthetic seismograms for the structural model shown in figure 3e.

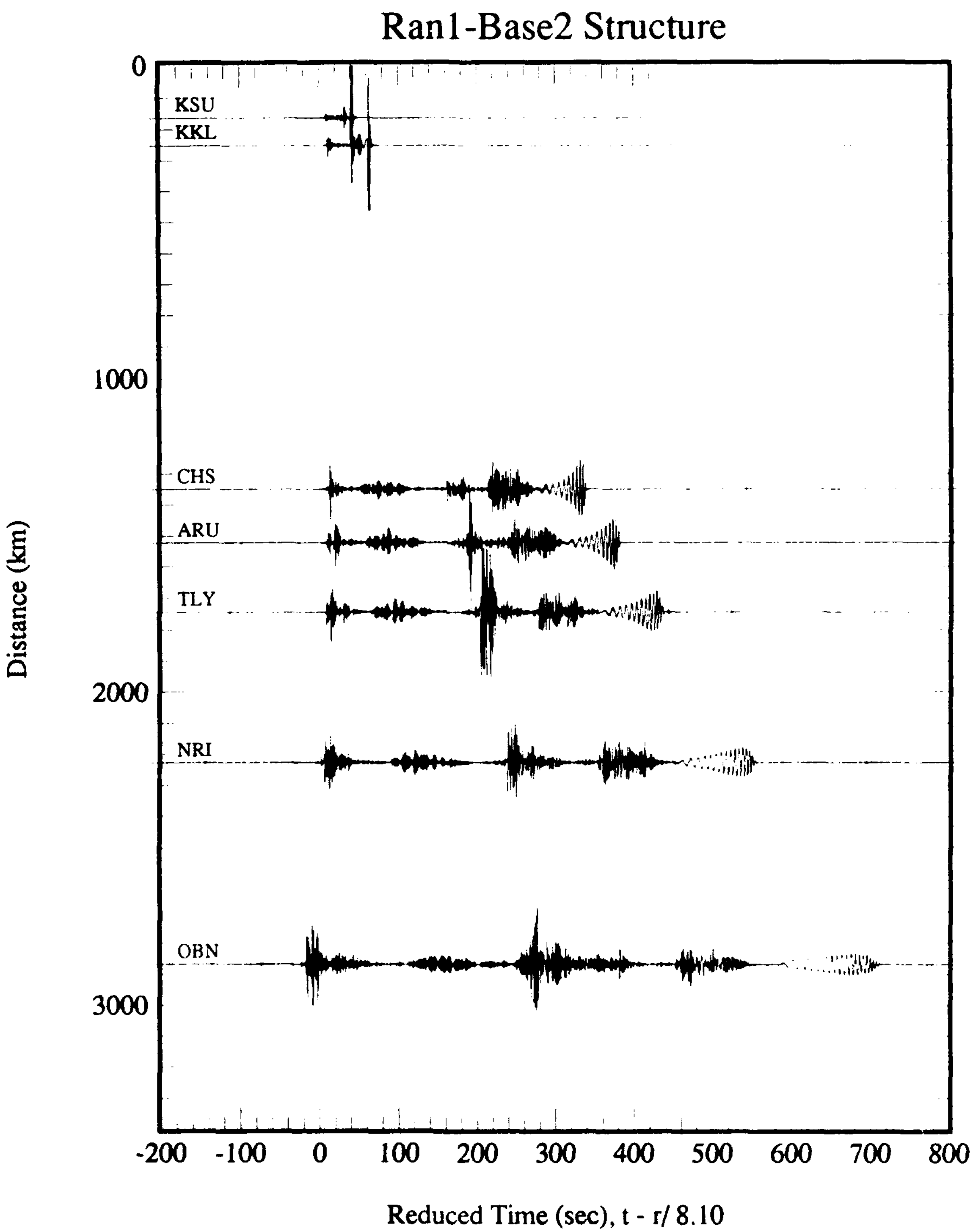

Figure 9. Synthetic seismograms for the structural model shown in figure 3f.

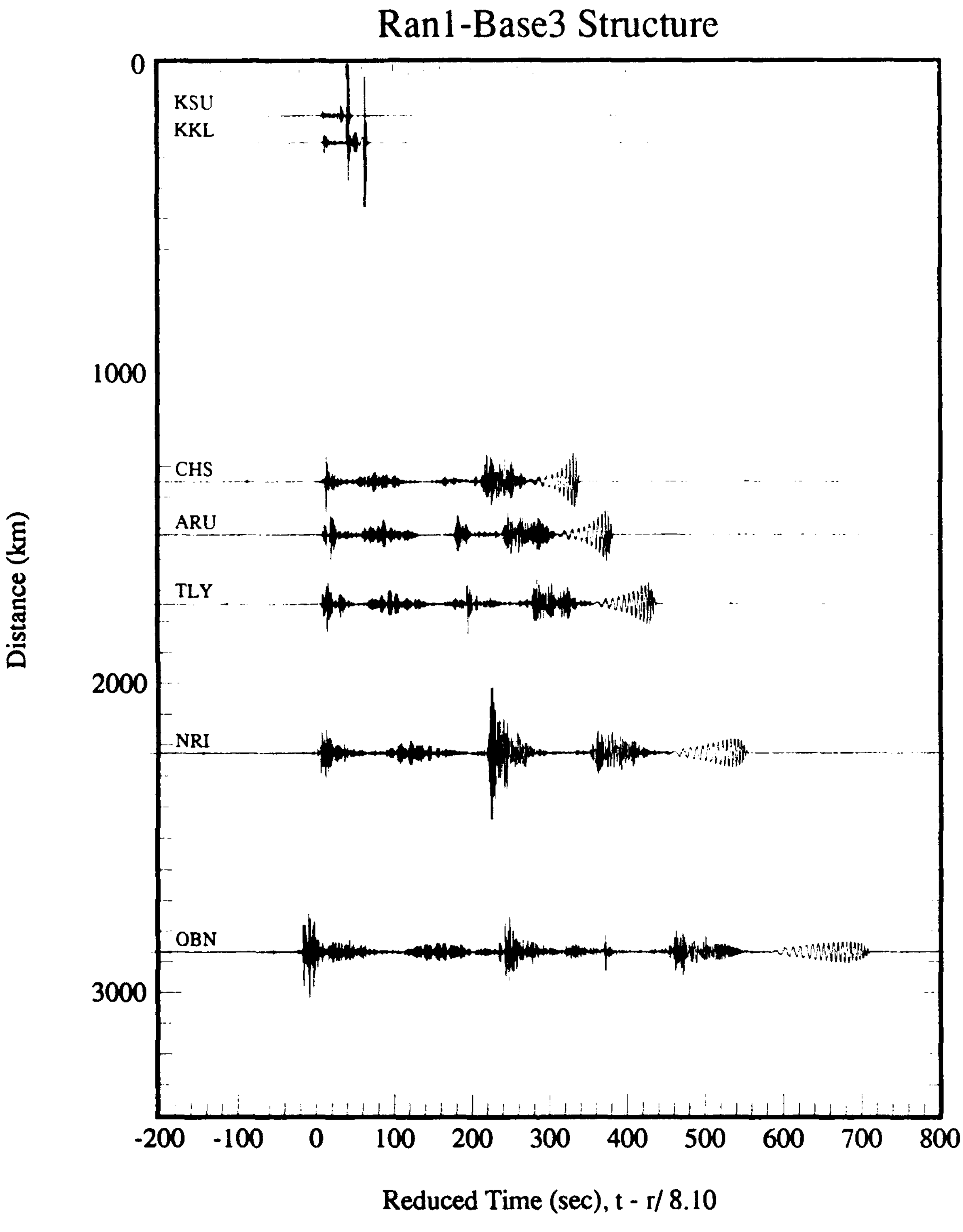

Figure 10. Synthetic seismograms for the structural model shown in fig. 3g.

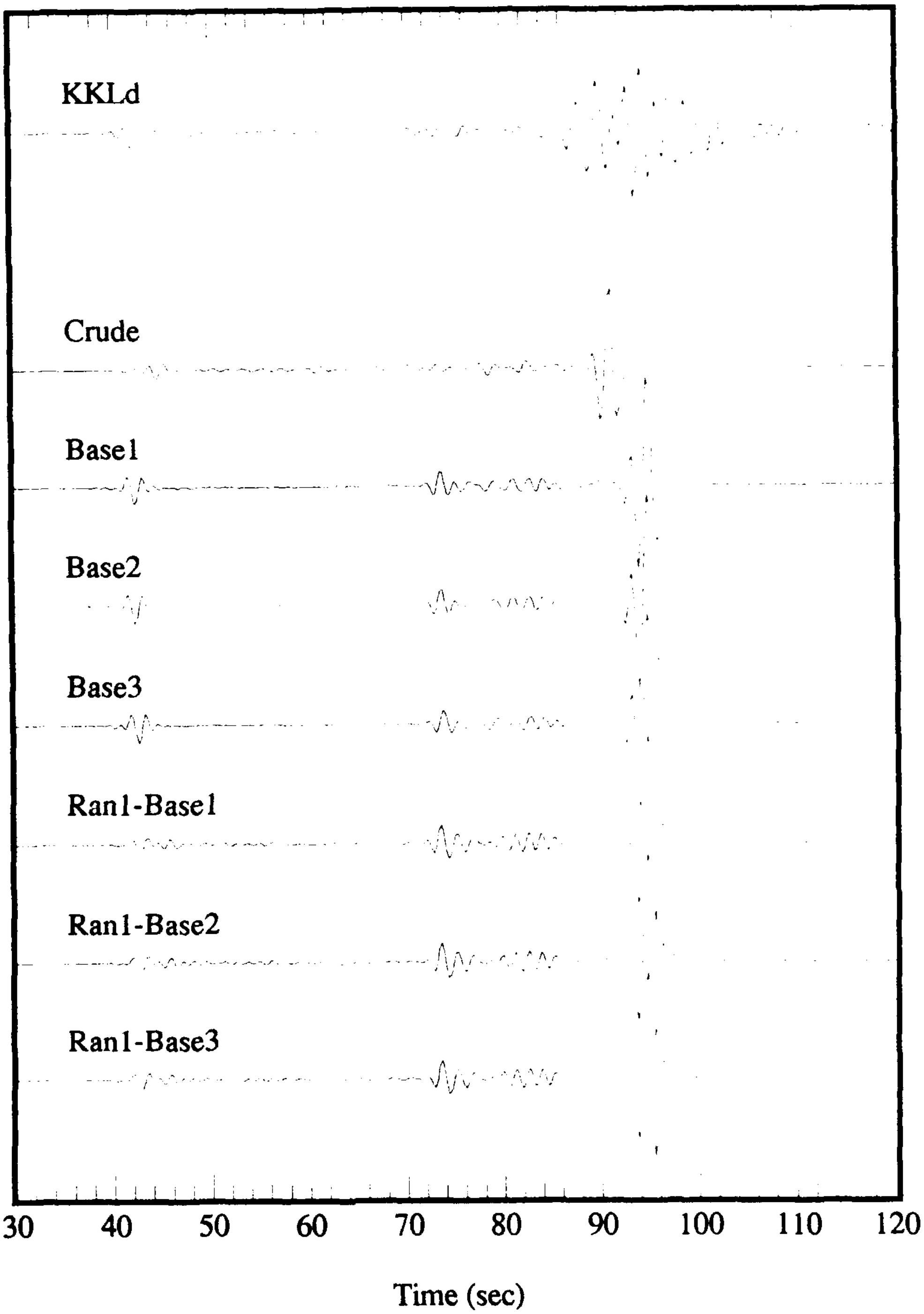

Figure 11. Comparisons of data with synthetic seismograms at KKL. The data station names end in "d" to signify the digital data or "a" to signify the analog data.

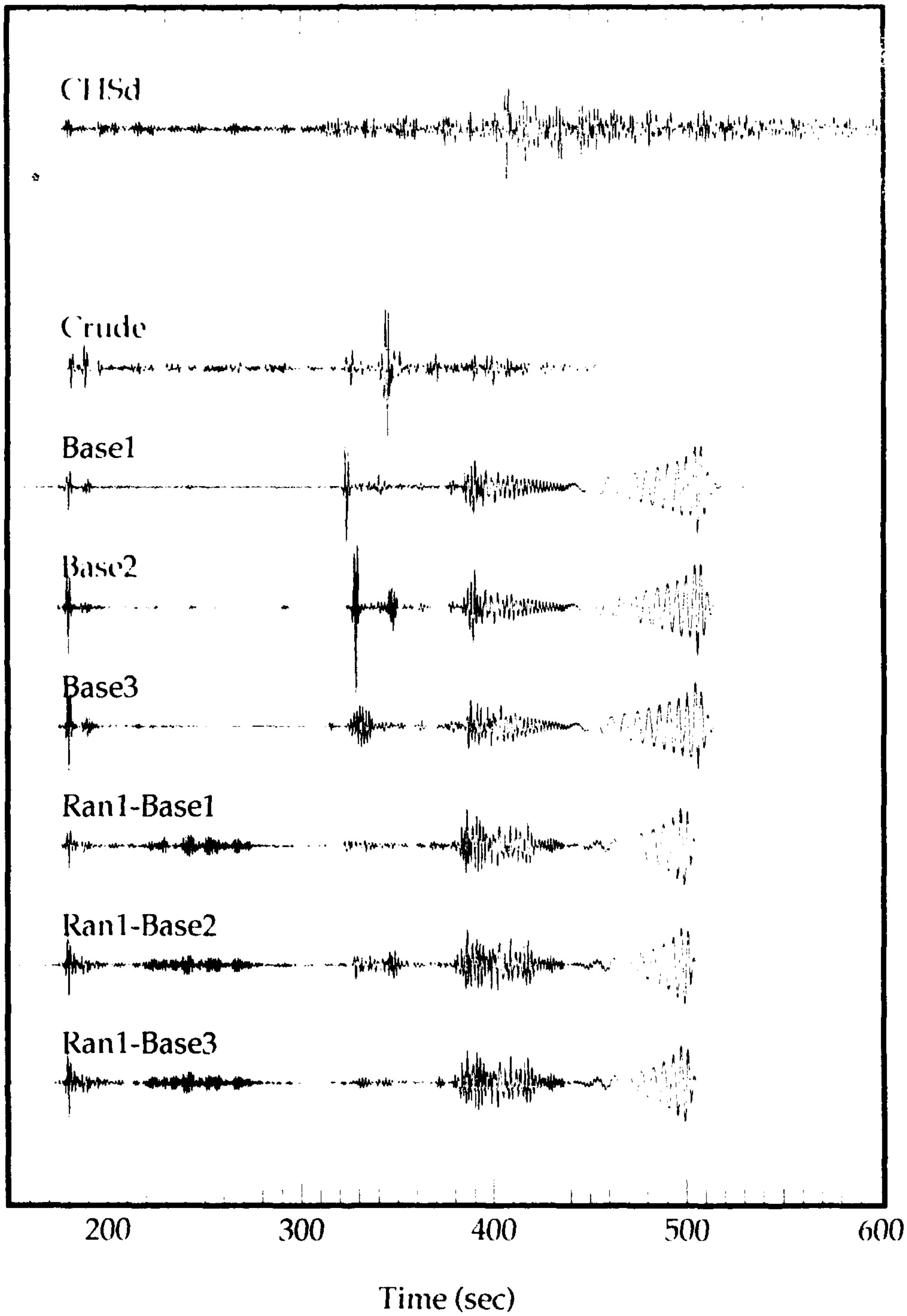

Figure 12. Comparisons of data with synthetic seismograms at CHS. The data station names end in "d" to signify the digital data or "a" to signify the analog data.

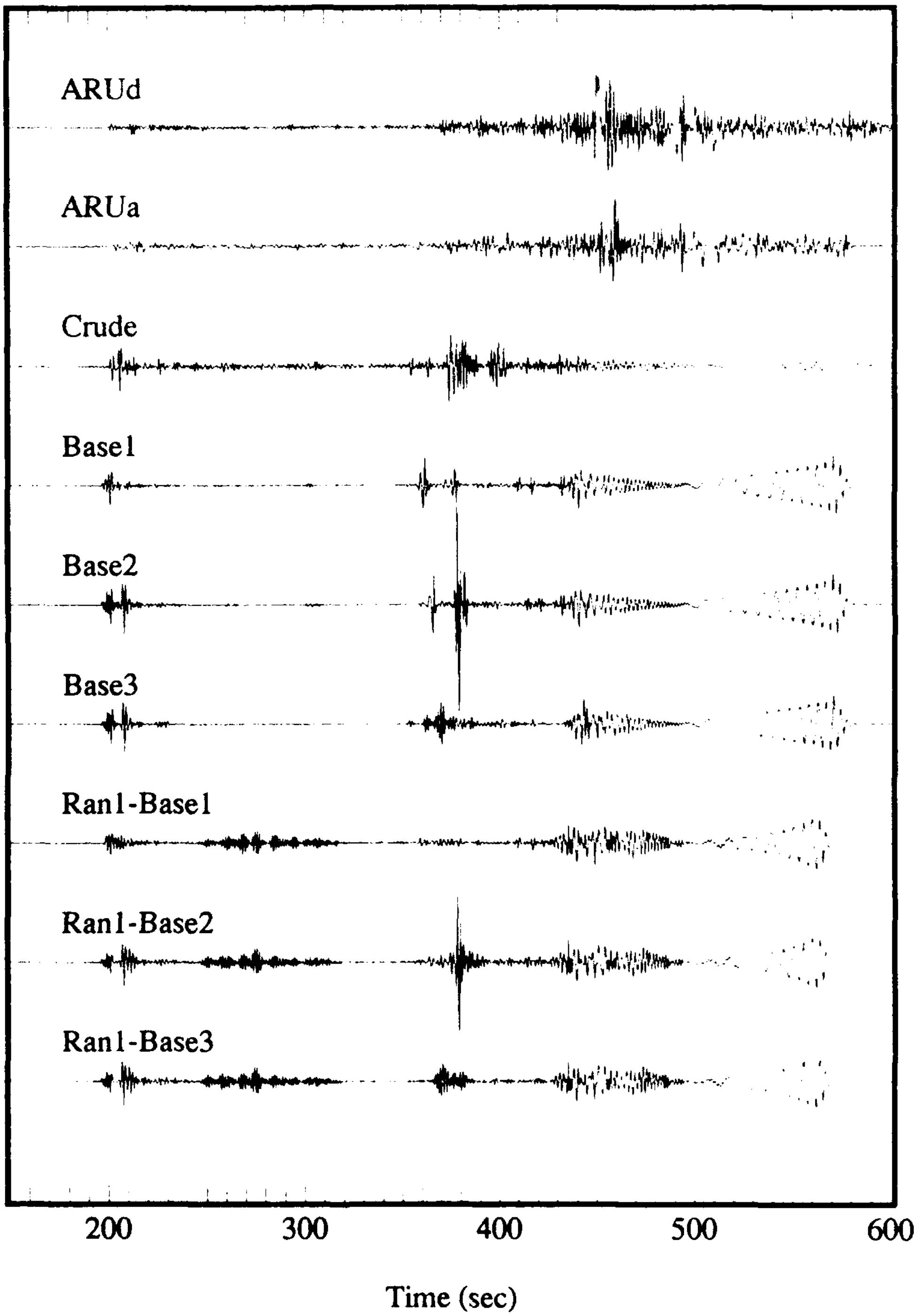

Figure 13. Comparisons of data with synthetic seismograms at ARU. The data station names end in "d" to signify the digital data or "a" to signify the analog data.

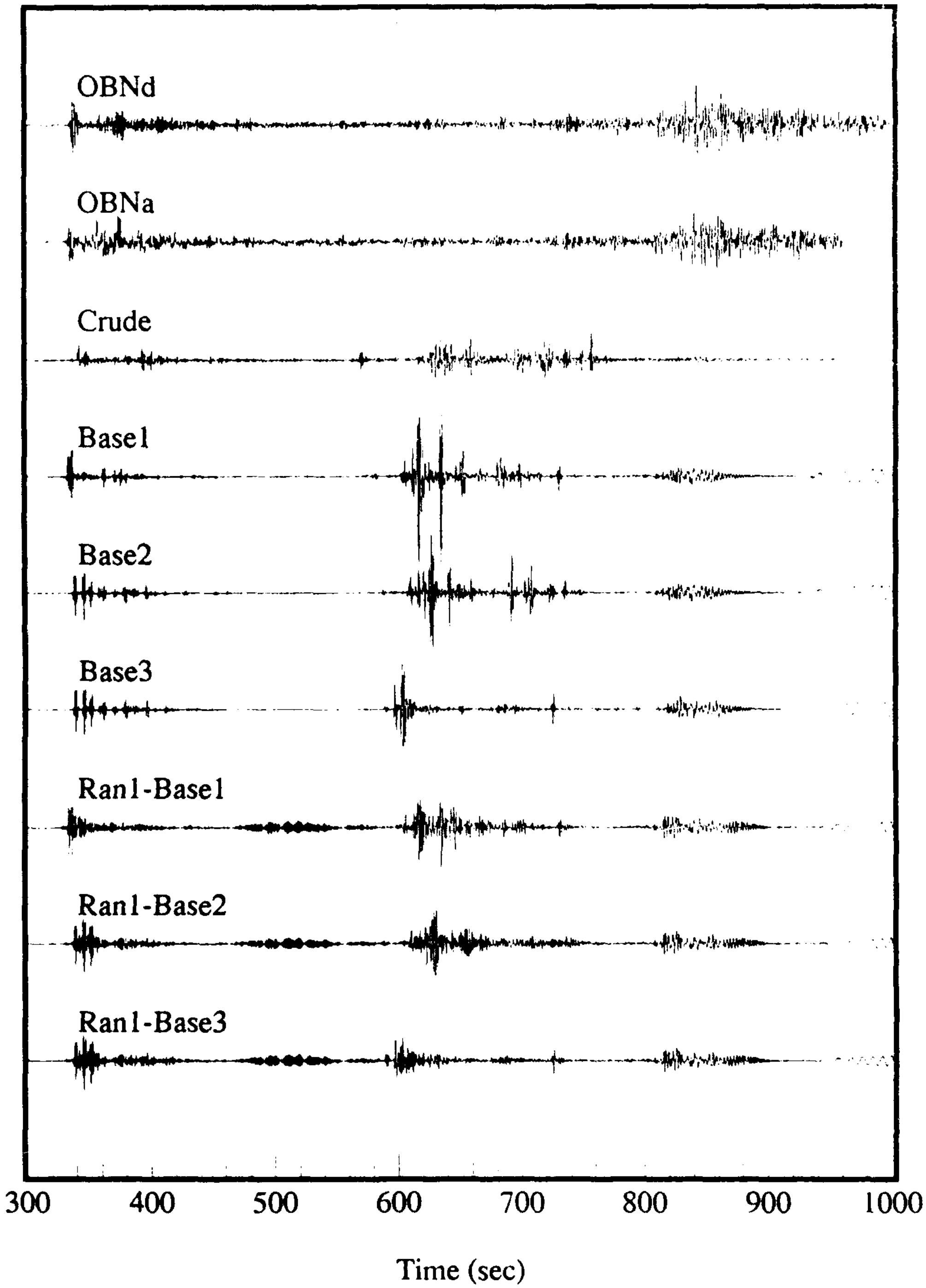

Figure 14. Comparisons of data with synthetic seismograms at OBN. The data station names end in "d" to signify the digital data or "a" to signify the analog data.

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